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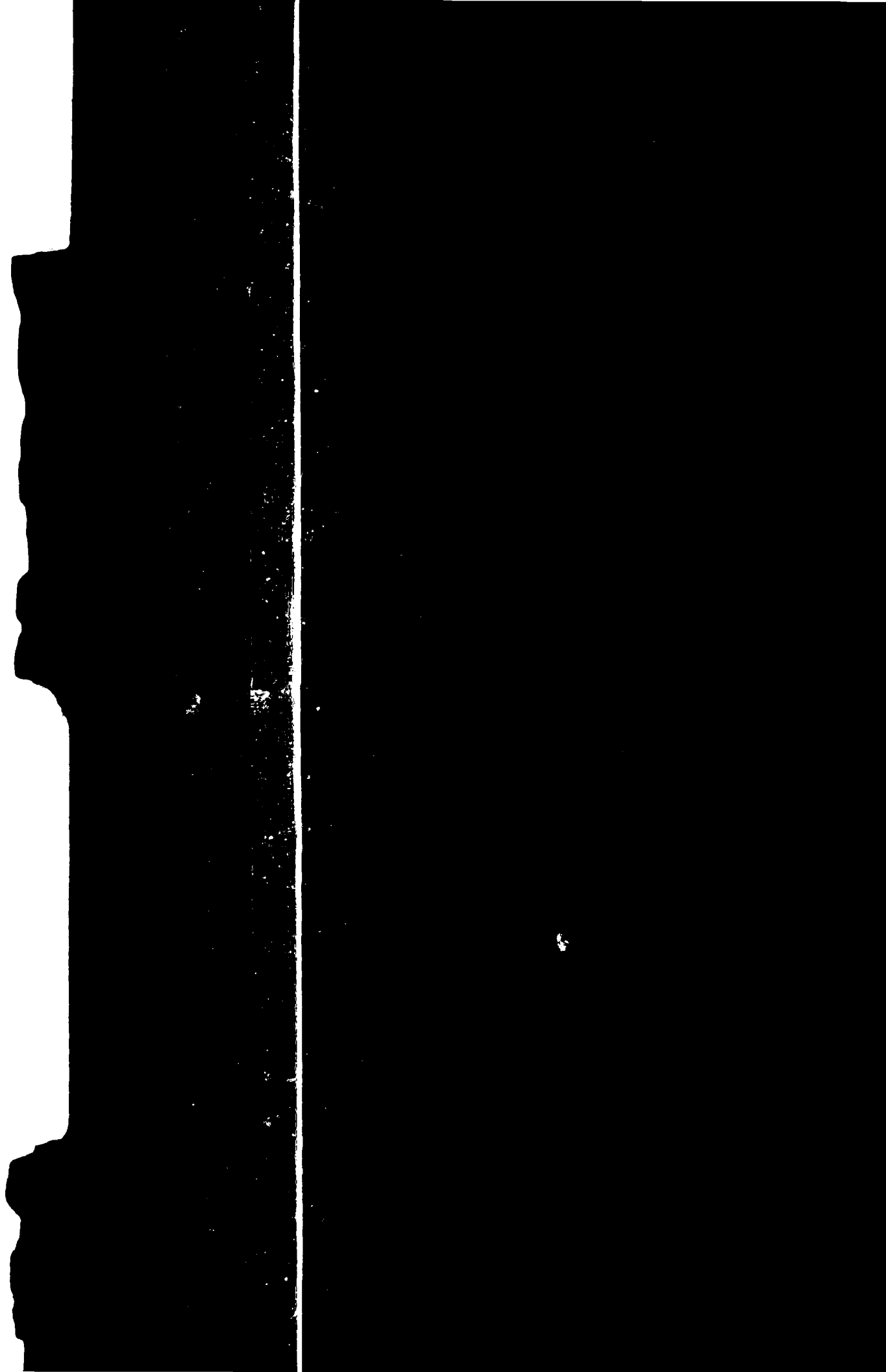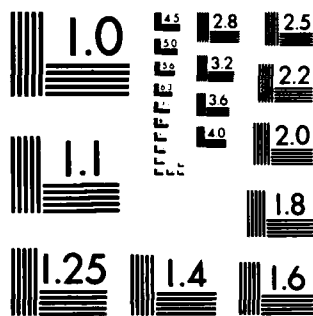
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HEATING OF THE DEEP CHROMOSPHERE
DURING SOLAR FLARES

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The role of the negative hydrogen ion, H^-, in the energy balance of the deep chromosphere is reassessed and quantitatively evaluated. We find that in quiet Sun conditions H^- is a <u>heating</u> agent, absorbing more photospheric radiation than it reradiates. We further propose that during flares a flux of UV radiation produces overionization of the deep chromosphere (principally by ionizing neutral silicon) and that the increased electron density

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so produced causes an increase in the $H + e \rightarrow H^+$ association rate and so an increased H^- abundance. The resulting increased absorption of photospheric radiation by the H^+ ions produces heating compatible with observations.

I. INTRODUCTION

It is by now well established through observation (e.g. Machado, Emslie, and Brown 1978; Cook 1979) that significant temperature enhancements ($\gtrsim 200$ K) are produced in the deep chromosphere at or around temperature minimum (height $h \approx 400$ km above the photosphere) levels during solar flares (Figure 1). Due to the great overlying mass of material ($m \gtrsim 0.1$ g cm^{-2}) at such levels, it has proved extremely difficult to reconcile these temperature enhancements with flare models in which energy is released in the corona and subsequently transported throughout the solar atmosphere by particles or radiation or both

In the discussion of the energy balance at such levels of the solar atmosphere, the role of the negative hydrogen ion, H$^-$, naturally arises. Its abundance is controlled principally by the *ionization of metals* (e.g. C, Si, ...), with subsequent association of the free electrons produced with neutral hydrogen atoms. H$^-$ represents a dominant source of opacity to photospheric radiation and it is therefore essential to determine accurately the radiative energy balance of H$^-$ in order to model the structure of the deep chromosphere.

In connection with our obligations under this contract, we have reexamined the role of H$^-$ in the deep chromosphere. We found that in quiet Sun conditions the radiative energy balance is such that H$^-$ represents a <u>heating</u> agent at these levels. In flares, however (when $T \gtrsim 4800$ K at the levels in question), the enhanced radiative <u>losses</u> from the H$^-$ continuum take over and the ion becomes a <u>cooling</u> agent. We were therefore led to the proposition that H$^-$ heating is responsible for raising the temperature of deep chromospheric layers to flare values ≈ 4800 K.
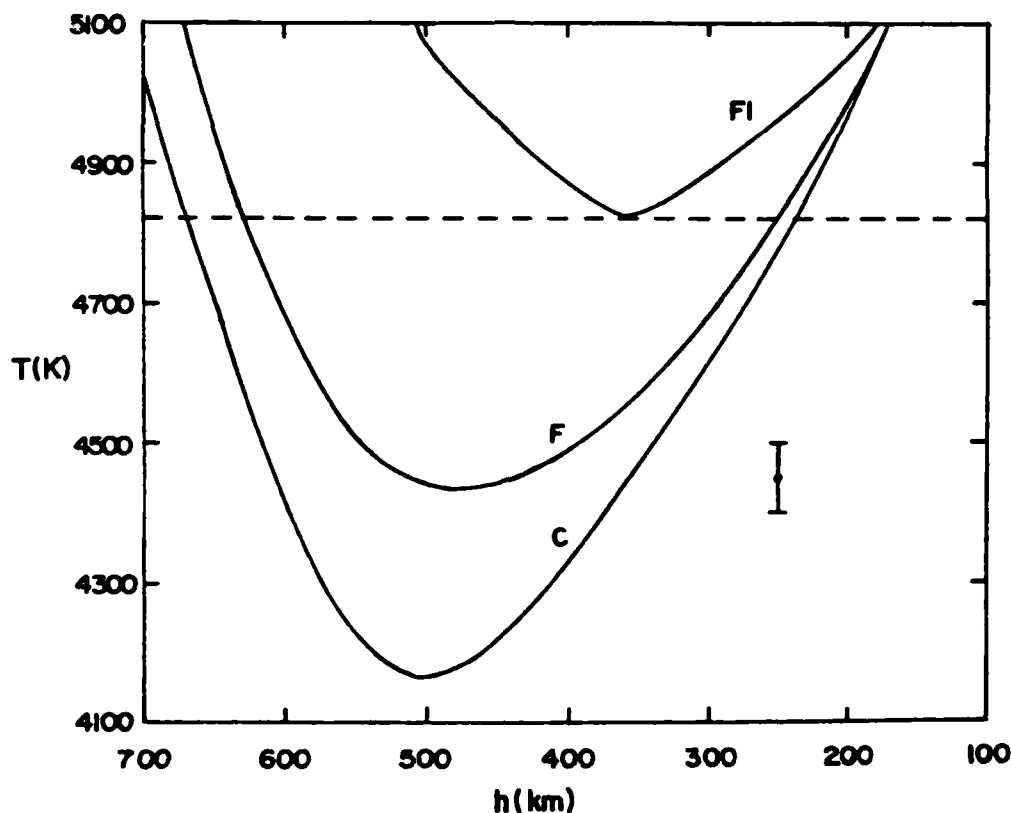
Figure 1. Empirical (i.e. observationally-deduced) models of the deep chromosphere, expressed as temperature (T) vs. height above photosphere (h). Models C and F are from Vernazza, Avrett, and Loeser (1981)- model C is an average quiet Sun model, while model F is a reasonable approximation to a preflare active region. Model F1 (from Machado et al 1980, Ap. J., 242, 336) is an averaged flare model. Note the strong temperature enhancements at h ≈ 400 km; no mechanism hitherto proposed has been able to account for these large enhancements. The dashed line at T = 4820 K divides the diagram into regions where the negative hydrogen ion is a heating agent (T < 4820 K) or a cooling agent (T > 4820 K); see Section II. Typical observational uncertainties are shown by the vertical error bar.

To address how the H^- heating may be enhanced, we investigated the effect of an enhanced UV radiation flux on the deep chromospheric layers. We found that significant photoionization of silicon could take place during times of flare-enhanced UV radiation; the resulting perturbed equilibrium of the $H + e \rightleftharpoons H^-$ reaction could lead to a significantly increased H^- abundance, an increased level of absorption of photospheric radiation, and so a heating of the temperature minimum layers of the atmosphere to values compatible with the observations of Machado, Emslie, and Brown (1978). We propose, therefore, that this mechanism indeed operates during solar flares – a finding that enhances our knowledge of energy transport in the flaring atmosphere and which is testable by further observation.

In Section II we summarize our findings on H^- energy balance. In Section III we consider the effect of an enhanced UV radiation field on the energy balance in the deep chromosphere, as discussed above. In Section IV we presend our conclusions.

This work has been submitted, in extended form, to the Astronomy and Astrophysics journal (Machado, Emslie, and Mauas 1984).

II. H^- ENERGY BALANCE IN THE DEEP CHROMOSPHERE

In this section we shall summarize the key results of our work. More details can be found in Machado, Emslie and Mauas (1984).

The net radiative energy loss (erg cm^{-3} s^{-1}) due to H^- is given by (Gebbie and Thomas 1970; Ayres 1980; Vernazza, Avrett, and Loeser 1981)

$$\Phi(H^-) = 4\pi \ (n^*_{H^-} \int_0^\infty \alpha_\nu L_\nu d\nu - n_{H^-} \int_0^\infty \alpha_\nu J_\nu^{\ O} d\nu), \qquad (1)$$

where n_{H^-} and $n^*_{H^-}$ are respectively the actual and LTE number densities of H^-, α_ν is the H^- photoionization cross-section

at frequency ν , J_ν^O is the mean photospheric radiation field intensity and

$$L_\nu = (J_\nu^O + \frac{2h\nu^3}{c^2}) \; e^{-h\nu/kT} \qquad , \qquad (2)$$

where h is Planck's constant, k Boltzmann's constant, T the temperature (K) and c the velocity of light. For conditions in the preflare temperature minimum layers, evaluation of (1) leads to $\Phi(H^-) < 0$; i.e. H^- is a source of radiative <u>heating</u> at these layers. In flare conditions, however, T is raised above quiet Sun values and it turns out that $\Phi(H^-) \lessgtr 0$ according as $T \lessgtr 4820$ K (for values J_ν^O from model C of Vernazza, Avrett, and Loeser 1981). It turns out (Figure 1) that this temperature is very close to actual temperature minimum values in flares, leading us to suspect H^- radiation heating as the cause of the temperature enhancements inferred from observation.

III THE EFFECT OF FLARE UV RADIATION

As pointed out by Emslie and Machado (1979), UV line radiation (particularly C IV $\lambda\,1548\,\text{Å}$) can penetrate the upper chromosphere extremely effectively, due to the lack of material with a suitably high opacity to such wavelengths at such temperatures. As the temperature falls to deep chromospheric values, however, the increased abundance of neutral silicon leads to a significant opacity at $\lambda\,1548\,\text{Å}$ through $3p^2\,^1D$ continuum photoionization of this species. Although Emslie and Machado (1979) have shown that a relatively small amount of energy actually resides in the photoelectrons produced by this process, so that UV radiation cannot <u>directly</u> supply the required energy to deep chromospheric levels during flares, Machado and Hénoux (1982) have shown that the photoionization caused by such radiation can have a profound effect on the electron number density at such levels (the hydrogenic electron contribution being negligibly small). These excess photoelectrons

are free to associate onto the large number of neutral H atoms present, thus increasing n_{H^-}, the number density of negative hydrogen ions. Since T is not significantly altered (only a small amount of _energy_ is deposited), $n^*_{H^-}$ remains the same, and so by equation (1), $\Phi(H^-)$ becomes more negative, i.e. excess heating results.
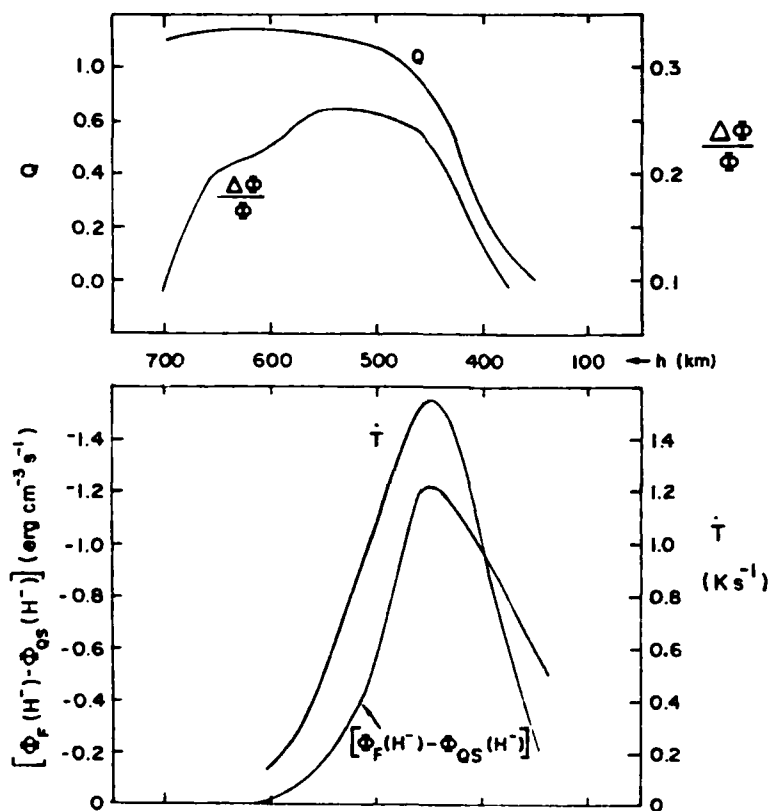

Figure 2. Top: Fractional ionization Q of silicon induced by a UV radiation flux of 1.2×10^6 erg $cm^{-2} s^{-1}$. The photo-electrons created associate with H atoms to produce H^-, resulting in an increased H^- heating rate $\Delta\Phi$, shown as a ratio of the quiet Sun value Φ.

Bottom: $\Delta\Phi$ in absolute units; also the corresponding temperature increase rate $\dot{T} = \Delta\Phi / (\frac{3}{2}nk)$. Note that $\dot{T}$ peaks at $h \approx 400$ km, exactly where the heating is needed to match observations (Figure 1).

We have evaluated the heating due to this mechanism (Figure 2) and find that significant temperature enhancements do indeed result at precisely the right atmospheric layers to explain the Ca II K-line observations of Machado, Emslie, and Brown (1978). As mentioned in Section II, such a mechanism can only raise T to ≈ 4820 K, after which H becomes a <u>cooling</u> agent. However, as discussed by Machado, Emslie, and Mauas (1984), other mechanisms (such as soft X-ray radiation - Machado, Emslie, and Brown 1978) can easily supply the remaining amounts of energy necessary to make the entire atmosphere structure compatible with empirical models inferred from flare spectra.

IV CONCLUSIONS

We have determined that an ionizing flux of UV radiation, comparable in intensity to fluxes found in typical solar flares, can photoionize sufficient silicon in the deep chromosphere to significantly enhance the electron number density at such levels. The photoelectrons created associate with H atoms to create H^- ions, which absorb photospheric radiation in sufficient amounts to explain the relatively large temperature enhancements found at deep chromospheric levels during flares.

The method discussed above is appealing, but so far lacks direct observational test. Such a test could consist of correlated C IV $\lambda 1548$ Å and Ca II K-line observations, to measure the change in deep chromospheric structure as UV radiation is supplied to these levels. The C IV observations are routinely made during periods of flare activity by the Ultra-Violet Spectrometer/Polarimeter (UVSP) on the recently repaired <u>Solar Maximum Mission</u> satellite. Observations of the $\lambda 4571$ Å line of neutral magnesium, by, for example, the tower telescope at Sacramento Peak Observatory, are also valuable in determining the structure of the temperature minimum layers. Such correlated UV/optical measurements provide a definitive test of the proposed mechanism and we encourage that they be carried out as soon as practicable.

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